U.S. Naval Air Development Center

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NADC-MR-6622 10 November 1966

A Quantitative Impedance Pneumograph

Naval Air Systems Command
Weptask R360 FR 102/2021/R01 101 01
(RF-5-01)

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DEPARTMENT OF THE NAVY
U. S. NAVAL AIR DEVELOPMENT CENTER
JOHNSVILLE
WARMINSTER, PA. 18974

Aerospace Medical Research Department

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SUMMARY

This report describes an impedance pneumograph capable of measuring quantitatively respiratory volumes. Features of this system include the use of a higher frequency (300 KHz) excitation voltage than is normally used in impedance pneumography and the use of pasteless electrodes which are insulated from the subject by a layer of polyethylene, thus forming a capacitive coupling of the electrodes to the subject and eliminating the problems associated with skin-to-electrode impedance changes. A near perfect empiric correlation was found to exist between the transthoracic impedance measured by this device and pulmonary volume.

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INTRODUCTION

Previous attempts have been made by a number of investigators to quantitatively correlate transthoracic impedance variations with respiratory volume changes. The advantages of the impedance technique are obvious: no restraint is placed on the subject; the entire system is small and light in weight and it can be worn for relatively long periods of time and used for a variety of applications. The technique described in this report has the following advantages over other impedance pneumography systems. The frequency of the alternating current applied to a pair of electrodes is considerably higher (300KHz) than that used by most experimenters (1, 2, 3). More importantly, the two electrodes are insulated from the subject's skin which results in a much more accurate indication of pulmonary volumes than the semiquantitative results described in previous reports. Variations in the impedance between skin and electrode, which bear little relevance to pulmonary variations, are eliminated by capacitively coupling the electrodes to the subject and thus the pneumograph measures only the impedance of the substance between the two electrodes. A near-perfect empiric correlation was found to exist between this transthoracic impedance and respiratory volumes.

This impedance pneumograph was designed to be compatible with a telemetry system capable of measuring other physiological parameters such as electrocardiogram (EKG), electroencephalogram (EEG), temperature, and blood pressure. The electrodes developed for both EKG and respiration were pasteless and therefore easily applicable, non-irritating, and capable of being worn for extended periods of time. Geddes, et al. (4) has described systems which use common electrodes for monitoring EKG and respiration. Since insulated electrodes could not be used for the relatively low frequency voltages of EKG, the telemetry system described herein utilizes separate electrodes for measuring respiration and EKG. It was felt that this method would not detract from the advantages of the system since the separate electrodes can be placed on the subject as a unit with the smaller EKG electrode placed in contact with the subject's chest.

CIRCUIT DESCRIPTION

Basically, the impedance pneumograph (Figures 1, 2) consists of a single transistor oscillator purposely designed "soft" so that a relatively small change in the load impedance will cause the amplitude of the output to vary considerably. The varying load impedance is comprised of the impedance between the two electrodes and varies with respiration. At the frequency used (300 KHz), the load impedance using the electrodes described is approximately 35 ohms. Respiration causes the impedance to vary slightly less than 1.0 ohm per liter. The varying amplitude 300 KHz signal is then demodulated using a half wave rectifier-filter, thus producing a direct current whose voltage is proportional to the oscillator's load. This DC output then can be used to drive a high impedance recorder directly or to drive a voltage-controlled sub-carrier oscillator for use in an FM-FM telemetry system. Telemetering the signal appears to be the most advantageous method in

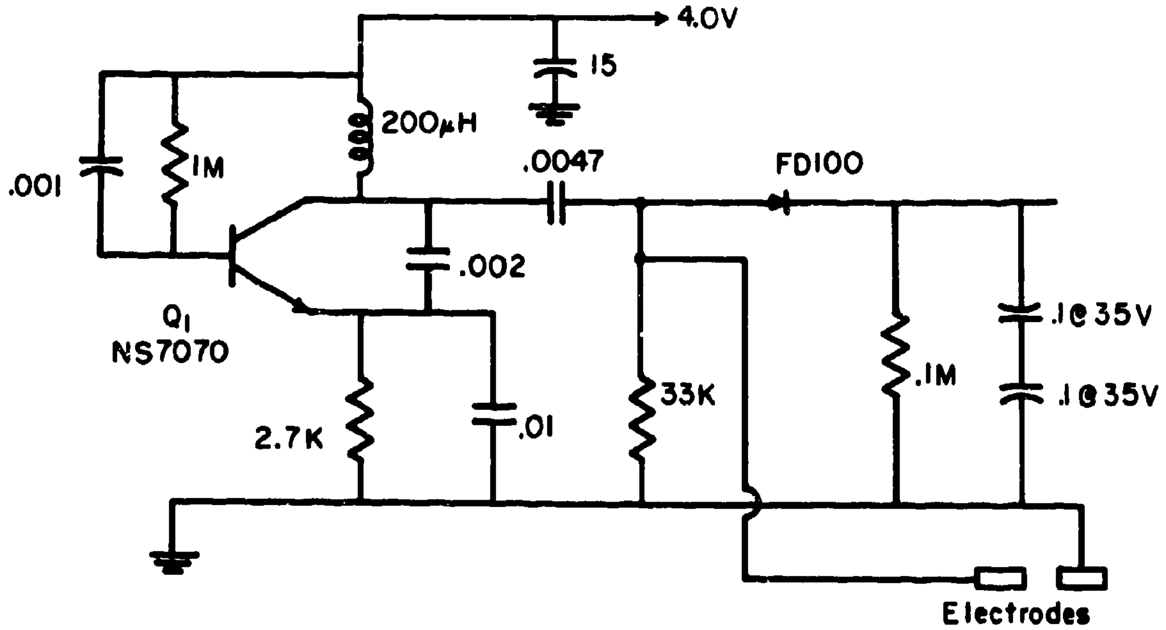

Figure 1. Schematic of impedance pneumograph. A modified Colpitts oscillator applies a 300 Kilohertz voltage to the body through a pair of insulated electrodes with variations in the impedance between electrodes causing amplitude modulation of the oscillator's carrier. These amplitude variations are extracted from the carrier by the diode and subsequent filter resulting in a DC signal whose voltage was empirically found to be proportional to pulmonary volumes. This varying voltage can be used to drive a subcarrier oscillator in an FM-FM telemetry system.

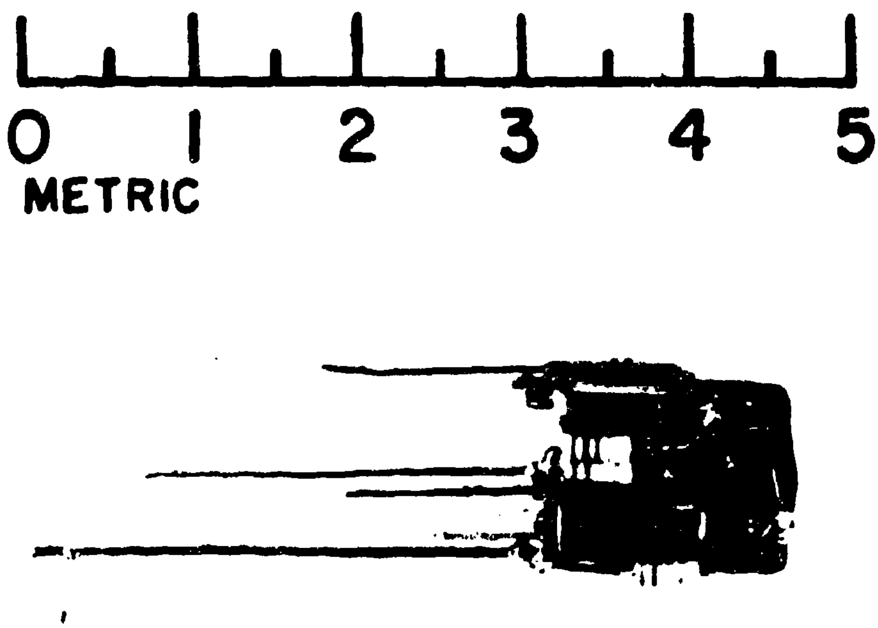

Figure 2. Use of a microtransistor and miniaturized components enable compact construction of the impedance pneumograph for applications where space is critical. This particular unit, after encapsulation in epoxy, measured 3/8 x 5/8 x 7/8 inches and was incorporated along with a number of other modules in a miniature biotelemetry system.

that artifact due to changes in the subject's position relative to ground are minimized. If the signal is coupled to a recorder directly, movement artifact results when one foot is raised off the floor, or when the subject changes his proximity to grounded equipment.

Considerable experimentation was done concerning the optimum frequency at which to operate the pneumograph oscillator. Previous attempts at impedance pneumography utilized frequencies in the 25 to 100 KHz range. It was felt that the use of a higher frequency would be advantageous in several respects. First, a higher carrier frequency requires less filtering to demodulate. Second, if other parameters such as EKG or EEG are being monitored simultaneously with respiration, a higher frequency will be more easily filtered out of the inputs to the other amplifiers, thus eliminating interference from the pneumograph oscillator. Third, in spite of the findings of previous investigators (5), the sensitivity of the pneumograph increased as the oscillator frequency was increased to about 360 KHz (Figure 3). Higher frequencies were tried with little success, possibly because of skin effect or some other phenomenon which altered the pathway of the RF radiated between the electrodes.

By comparing Figure 4 with Figure 5, it can be seen that not only does the sensitivity of the pneumograph decrease at lower frequencies, but also the accuracy of the output as an indicator of respiratory volumes is poorer.

The circuit shown in Figure 1 produces a 4 volt peak-to-peak sinusoidal potential between the two insulated electrodes. The voltage required for accurate results from the pneumograph varies with the physical habitus of the subject, size of the electrodes, and frequency of the oscillator. In order to minimize interference with the simultaneous measurement of other physiological parameters, the voltage applied to the electrodes should be kept as low as is necessary to obtain accurate results. With the system described in this report, the optimum voltage, with respect to accuracy and interference, was found to be the 4 volts peak-to-peak mentioned above. With the electrodes in place on the subject, the transthoracic impedance loads the oscillator and the voltage is reduced to approximately 3 volts peak-to peak depending on the physical habitus of the subject.

Voltages lower than 4 volts peak-to-peak proved unreliable on all but the thinner subjects. Increasing the voltage beyond 4 volts peak-to-peak did not significantly improve the accuracy of the output and beyond 18 volts peak-to-peak accuracy declined, and, of course, interference with other channels became intolerable.

ELECTRODES

Previous attempts to measure respiratory volumes with impedance devices have utilized electrodes placed in direct contact with the subject's skin to measure transthoracic impedance. To eliminate the variation in electrode-skin impedance the electrodes of this system were insulated from the subject's skin with a thin polyethylene film, thus forming a capacitive coupling of the electrode to

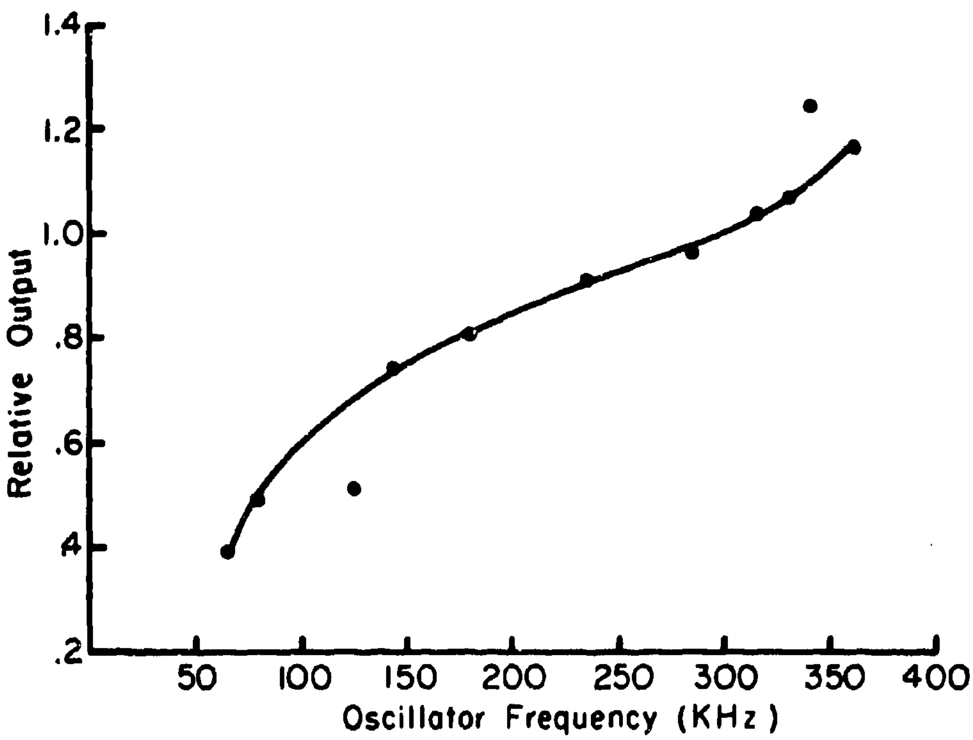

Figure 3. Attenuation of output as a function of oscillator frequency. The voltage between electrodes is 4 volts peak-to-peak for all frequencies.

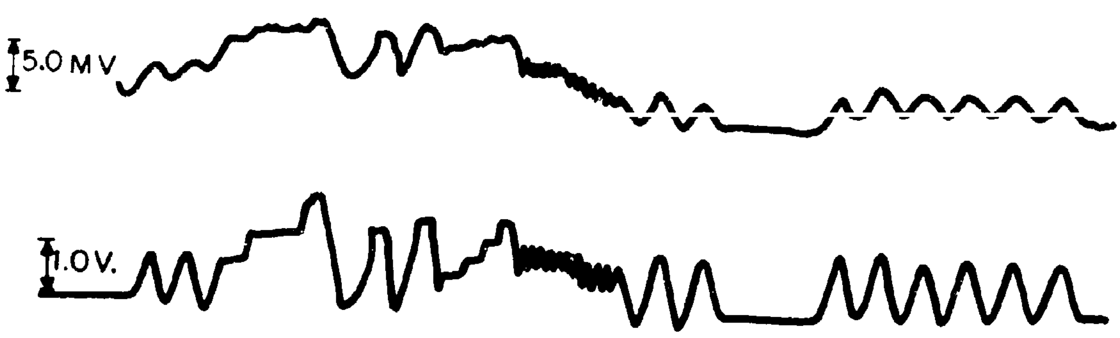

Figure 4. Respiratory volume versus time as recorded simultaneously by the standard spirometer (bottom trace) and an impedance pneumograph using a 78 KHz voltage. In comparison with Figure 5, a decrease in sensitivity and output accuracy can be seen.

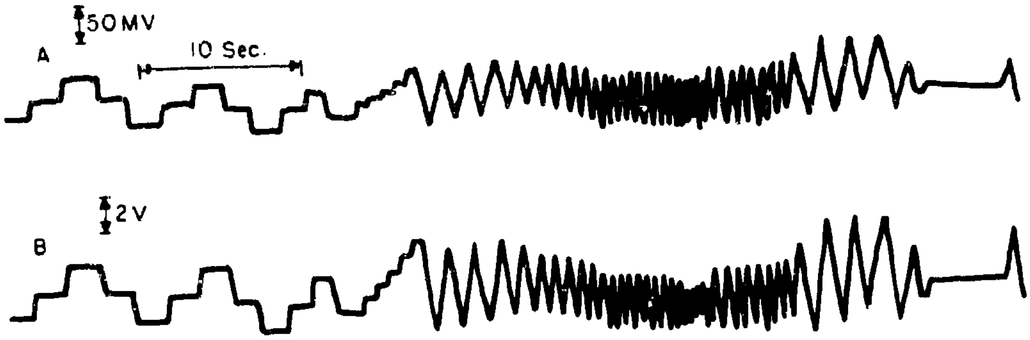

Figure 5. Respiratory volume versus time as recorded simultaneously by the impedance pneumograph (Trace A) and the standard spirometer (Trace B). The subject purposely varied his respiration so as to include a wide range of volumes and respiratory rates. The pneumograph oscillator frequency was 300 KHz with 4 volts peak-to-peak applied across the electrodes.

the subject. Since the skin-to electrode impedance is now a constant high impedance, the oscillator load varies only with the impedance between electrodes and proportionally with the volume of air in the lungs. Also, baseline drift, normally due to skin-to-electrode impedance changes, was entirely eliminated.

The electrodes for the impedance pneumograph were constructed of silver coated nylon.* Each electrode was constructed of two 4-3/4 inches x 6-3/8 inches rectangles fastened together along all four edges with a strip of cotton edging 1/2 inch wide. Electrical connection was made to the metallized cloth by soldering lengths of 24 gauge stranded, plastic insulated wire to a size 15 snap fastener inserted through one corner of the electrodes approximately 1/2 inch from 2 edges (Figure 6).

These electrodes were then sealed in small polyethylene sandwich-wrapping bags called "Baggies"** to insulate the electrodes from the subject. The only disadvantage of this method is that the large area of polyethylene covering the subject's skin causes uncomfortable perspiration. This problem presumably could be avoided if the electrodes were woven of filaments of polyethylene-coated silver, but, to date, such a material has not been available.

The electrodes were placed transthoracically on the midaxillary line with the top edge of each electrode placed at the level of the lower edge of the areole. Smaller electrodes were more subject to artifact resulting from arm movement and pressure on the electrodes. Larger electrodes produced a nonlinear output at extremes of the respiratory cycle, presumably because of the interposition of various internal organs; e.g., the liver.

One of the pneumograph electrodes is connected to the ground point of the oscillator (Figure 1). If the oscillator is placed in, and grounded to, a metal case, such as in the system described, care must be taken to separate the metal case from the subject so that it will not act as an extension of the grounded impedance pneumograph electrode. The aluminum cases were insulated from the subject's chest by a 1/2 inch thick layer of polyurethane foam and the denim vest. An alternative approach would be to avoid connections between the pneumograph oscillator and its case.

VESTS

A unique feature of the overall telemetry system involves the use of a vest to hold the pasteless EKG and respiration electrodes in place on the subject. Two pockets in the front of the vest hold the packages containing the transmitter, amplifiers, impedance pneumograph, and VCO's.

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* Prodesco, Inc. Perkasie, Pa. Silver coated nylon type PNAS #71
** Colgate-Palmolive Co., New York, N.Y.

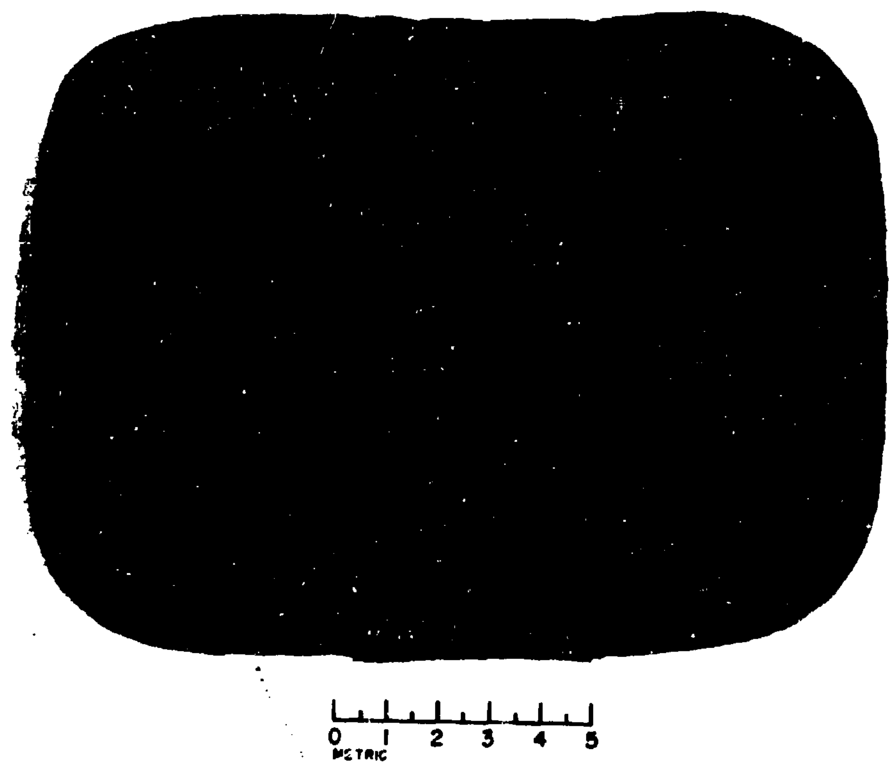

Figure 6. Single electrode for pneumograph before enclosure in polyethylene bag. Snap fastener in upper left corner is used for connection of leads to oscillator. Scale is calibrated in centimeters.

Three types of vests have been designed and fabricated. A prototype, constructed of "rigid" denim was not found to be compliant enough; that is, it restricted the subject's chest movement somewhat. As a result, the output of the impedance pneumograph attenuated progressively with an increase in respiratory rate and became distorted above approximately thirty breaths per minute. Proof that these effects were due to the relative inelasticity of the vest was obtained by cementing the electrodes to the subject's skin; the amplitude and wave form of the pneumograph were near-perfect regardless of respiratory rate. Although cementing may be suitable for certain long term studies, a more elastic vest as described below would probably be more convenient for most applications.

The vest shown in Figures 7 and 8 was fitted for one subject and constructed of one-way stretch denim which presented less restriction to breathing than the earlier version. The use of elastic brassiere expanders on each side of the vest added to its compliance and the hook fasteners on these elastic strips facilitated removal of the vest. A zipper up the back was used to pull the vest snug on the subject.

Although this tailor-fitted vest produced very satisfactory results, it was not suitable for testing the pneumograph on a wide variety of subjects. A more universal model was constructed of Lycra and stretch denim to fit practically any subject. As with the elastic vest described above, this abbreviated version, shown in Figures 9 and 10, was used to hold the EKG and pneumograph electrodes in place on either side of the subject.

At normal respiration rates (i.e. 10-25 breaths/min) this universal vest proved as successful as the fitted vest, but at high rates of respiration, some attenuation was noted in the output of the pneumograph due to the fact that this universal vest did not fit all subjects perfectly; that is, the pressure applied to the pneumograph electrodes was not exactly correct. Figure 11 shows the average attenuation encountered when eight subjects wore the universal vest.

Evidently, pressure on the pneumograph electrodes is fairly critical for accurate results, therefore, if precise results are to be obtained, it is recommended that each subject be fitted with a suitable vest such as the one shown in Figure 7. If, however, a large number of subjects are to be experimented with, and slight inaccuracies at fast respiration rates can be tolerated, then the vest shown in Figure 9 would probably be more convenient.

CALIBRATION PROCEDURE

In order to determine any correlation between the output voltage of the impedance pneumograph and the volume of air contained in the subject's lungs, a method of simultaneously recording respiratory volume as indicated by a standard and by the impedance pneumograph was required. This was accomplished by recording the respiration of a quietly-sitting subject with a recording wedge spirometer*,

*Med-Science Electronics Co., St. Louis, Mo. Hi-Fi Spirometer Model 470

Figure 7. "Tailor-fitted" vest showing electrodes on either side. Smaller electrodes are for EKG, larger electrodes, enclosed in plastic bags are for the impedance pneumograph. The transmitting antenna is shown taped to the vest above the transmitter package.

Figure 8. Subject in vest showing telemetry packages. Left pocket encloses the FM transmitter; right pocket holds amplifiers and VCO's.

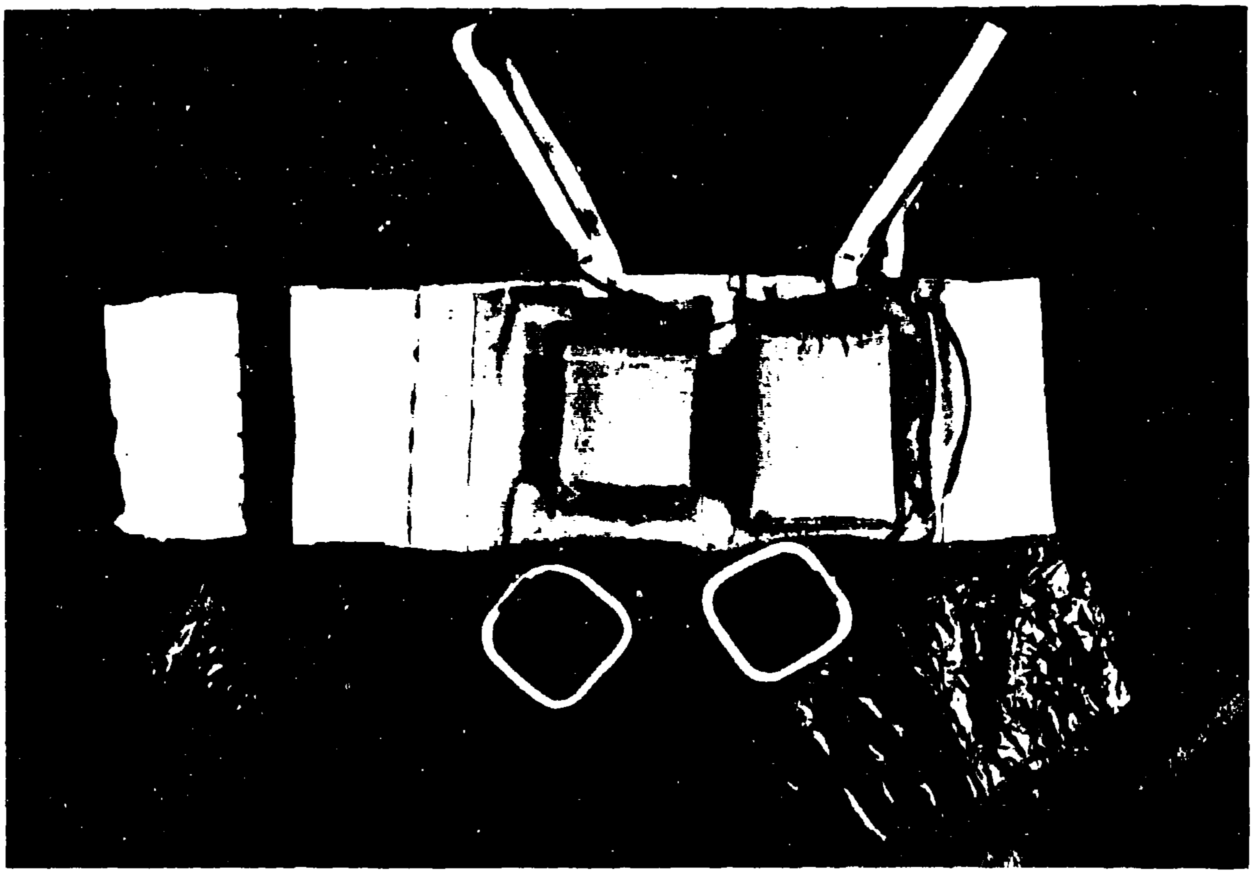

Figure 9. Universal vest with telemetry packages in pockets. To the left of the vest is shown one of several expandable panels which can be inserted in the side of the vest to increase its size.

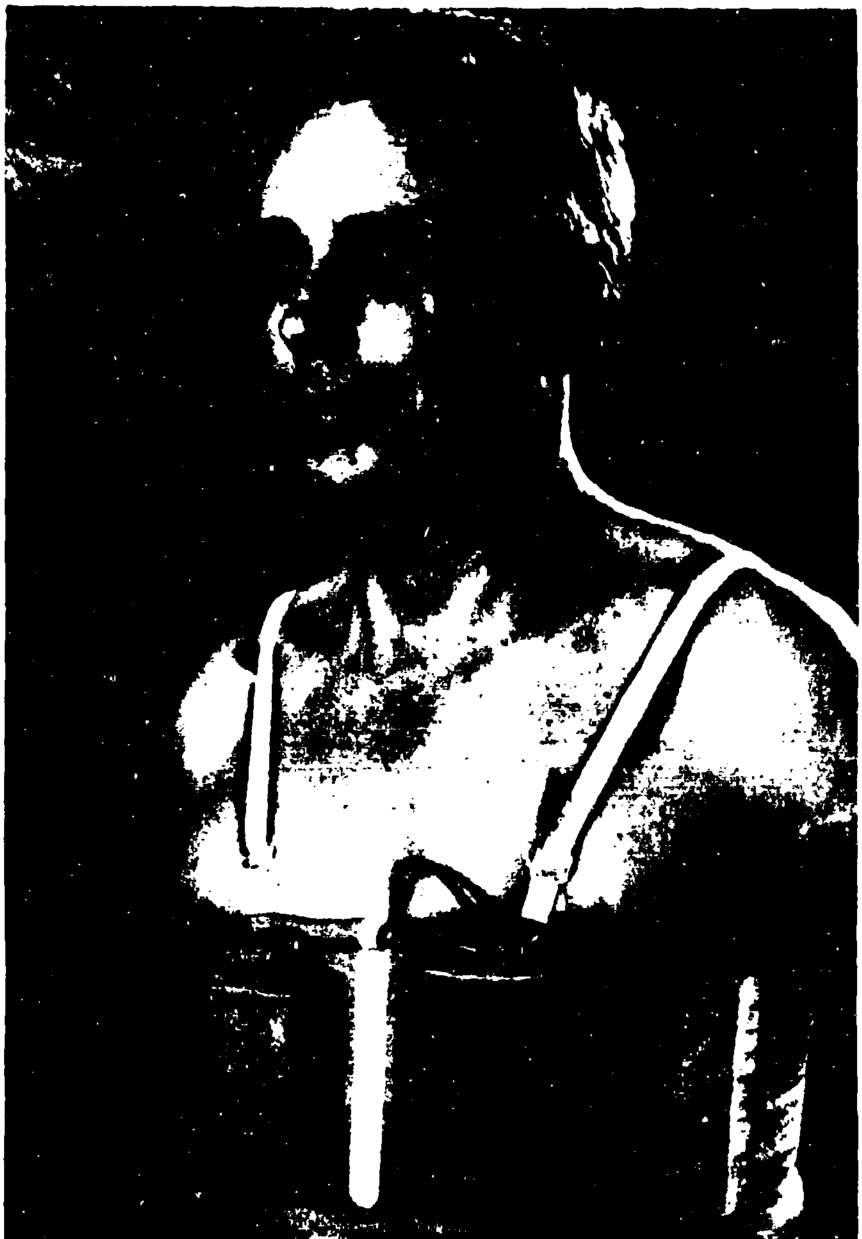

Figure 10. Subject in universal vest.

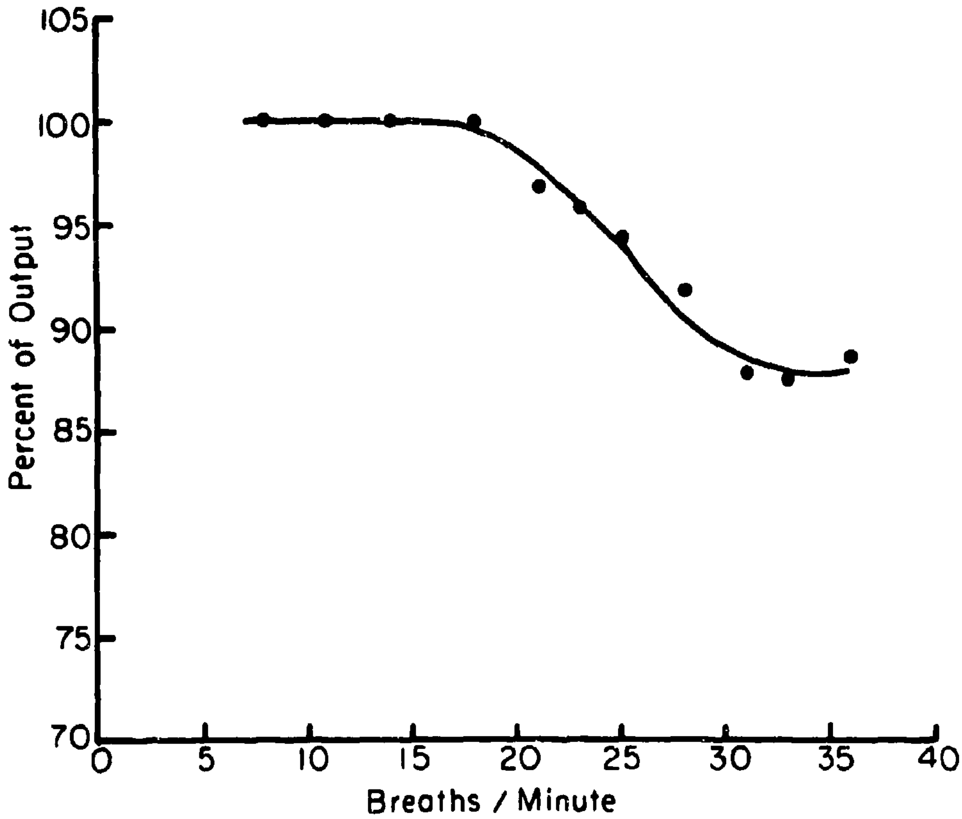

Figure 11. Reduction of pneumograph output at high respiratory rates. This is the average attenuation encountered when eight subjects wore the universal vest shown in Figure 9. The deviation from this mean never exceeded 10%. This graph is intended to be used in conjunction with Figure 13 to indicate approximately how much attenuation can be expected when any subject has his respiration monitored using the "universal" vest. Thus, for example, at thirty breaths per minute, one can expect that the voltage change per liter, using the universal vest, will be approximately 89% $\pm$ 10% of that shown in Figure 13. If proper consideration is given to pressure applied to electrodes by using a "tailor-fitted" vest, 100% output can be expected for any respiratory rate.

the output voltage of which varies linearly with volume. This output voltage was previously calibrated in terms of volume, as shown in Figure 12, by introducing into the spirometer known volumes of air from a calibrated cylinder*, enabling this spirometer to be used as a primary standard for all subsequent calibrations. The output voltage of the impedance pneumograph was plotted versus the volume of respired air and a linear relationship was found to exist as is indicated in Figure 13. Figure 5 is a plot of volume versus time as recorded by the impedance pneumograph and the spirometer under static conditions.

RESULTS OF IMPEDANCE PNEUMOGRAPH EXPERIMENTATION

Position and Weight of Subject

The position of the subject was not found to have any effect on the linear response of the pneumograph to respiratory volume, although the relative output of the pneumograph for a given volume change was affected as indicated on the following chart:

POSITION OF SUBJECT	RELATIVE OUTPUT (STANDING-1.00)
Standing	1.00
Sitting	.78
Lying on back	.71
Lying on "hot" electrode	.36
Lying on common electrode	.78

Similarly, the relative output of the pneumograph varies depending on such physical characteristics of the subject as chest circumference and amount of subcutaneous fat.

Apparently, the relative sensitivity was affected largely by the pressure applied to the electrodes which in turn was affected by the weight of the subject.

Baseline Shifts due to Leg Raising, Mueller and Valsalva Maneuver

With the subject lying on his back and holding his breath, a deflection of baseline was noted when his legs were raised. As shown in Figure 14, this deflection was in the direction of an inspiration (decreased impedance) and was presumably caused by an increase in pulmonary blood volume. In support of this theory, Figure 15 shows a similar deflection caused by the subject performing a Mueller maneuver and an opposite deflection which was caused by the subject performing a Valsalva maneuver which causes a decrease in pulmonary blood volume.

*George K. Porter Co., Hatfield, Pa. Vol-u-meter

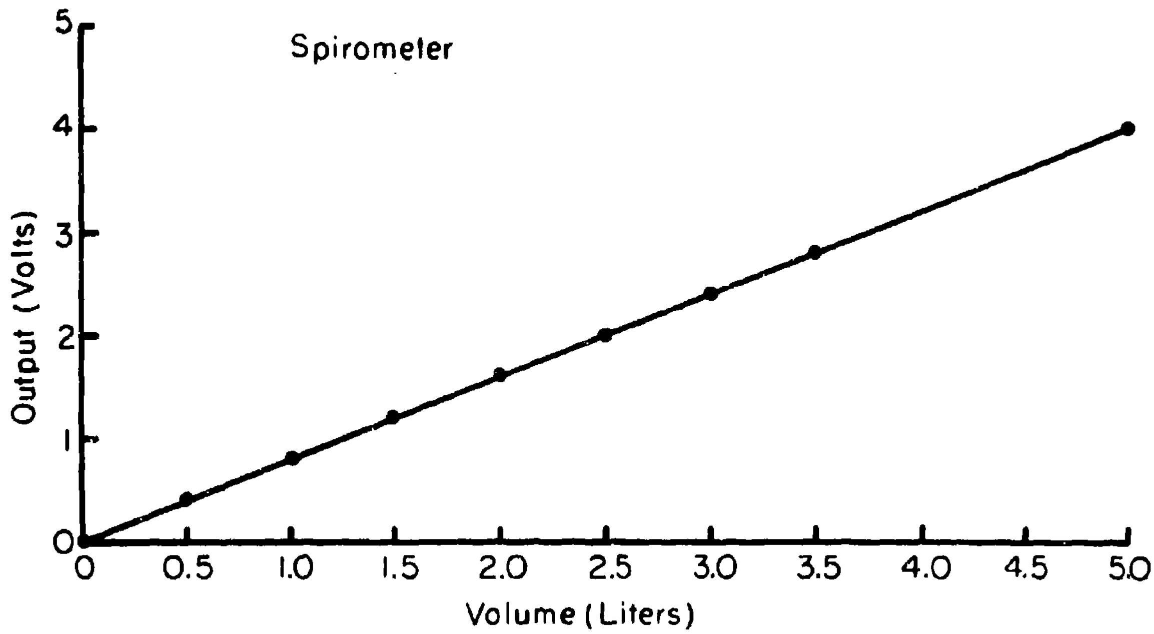

Figure 12. Calibration curve for the spirometer to be used as the primary standard.

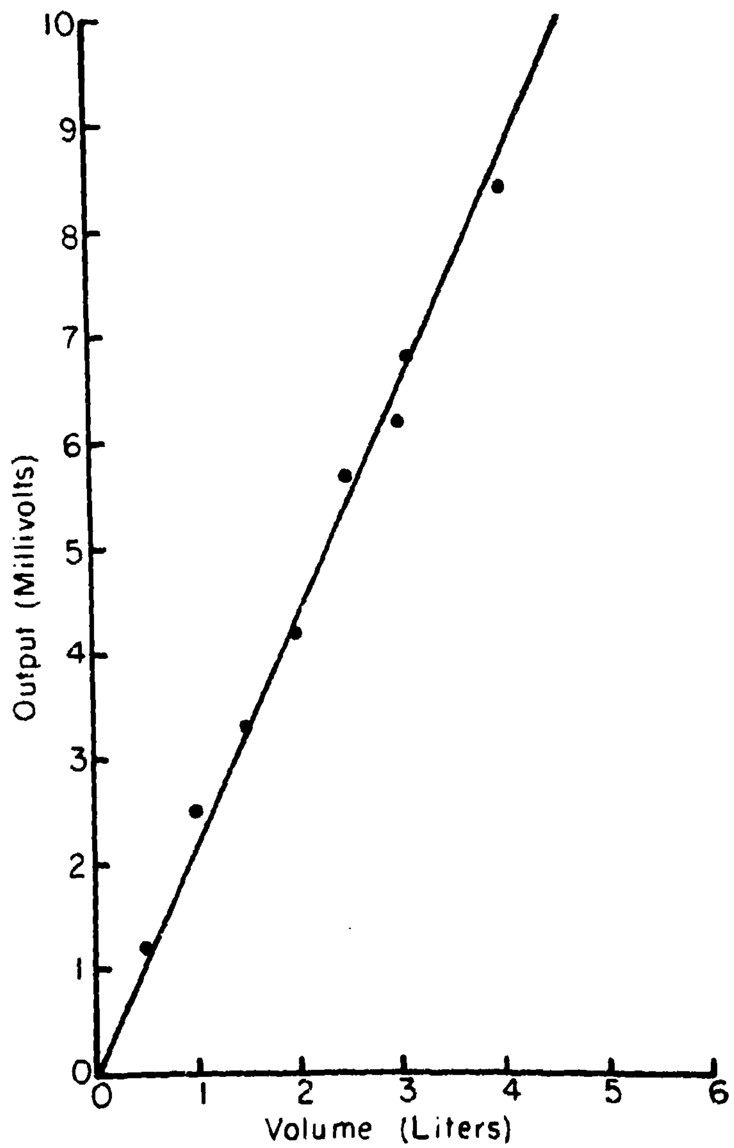

Figure 13. Calibration curve for the impedance pneumograph shown in Figure 1.

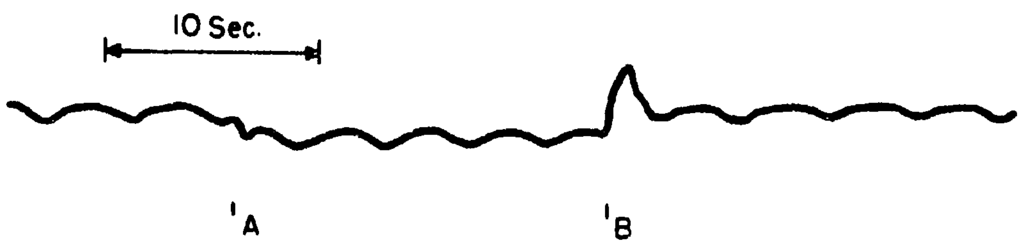

Figure 14. Impedance change caused by raising the legs of a subject lying on his back. During the interval from A to B, the subject held his breath while his legs were passively raised. The downward deflection indicates a decrease in impedance between electrodes.

Figure 15. Impedance changes caused by the subject performing a Mueller maneuver (interval A to B) and a Valsalva maneuver (interval C to D).

Effects of Dielectric

The manner in which the metallized cloth electrodes were insulated from the subject's skin proved to be quite critical for reasons which are not yet explainable. The majority of the experiments performed with the pneumograph utilized the polyethylene bags as the dielectric material. Several variations of this method were tried with drastic changes in the accuracy of the pneumograph output. For example, the interposition of three layers of surgical gauze between the plastic and the subject's skin resulted in an output that was "clipped" at both inspiratory and expiratory extremes as is shown in Figure 16. A similar interposition of two additional layers of polyethylene film in place of the gauze produced similar distortions of output.

DISCUSSION

The exact nature and cause of the variations in transthoracic impedance measured by this device have not yet been ascertained. Other investigators have reported (5) that the primary component of the impedance which varies with respiration is the resistance while the reactive component remains essentially constant. Other speculations implicate variations of blood volume in the chest, air in the lungs, or lung tissue density as being responsible for the impedance changes noted (2, 6, 7). In any case, the impedance between the electrodes as measured with the pneumograph, varies linearly with the volume of air in the lungs.

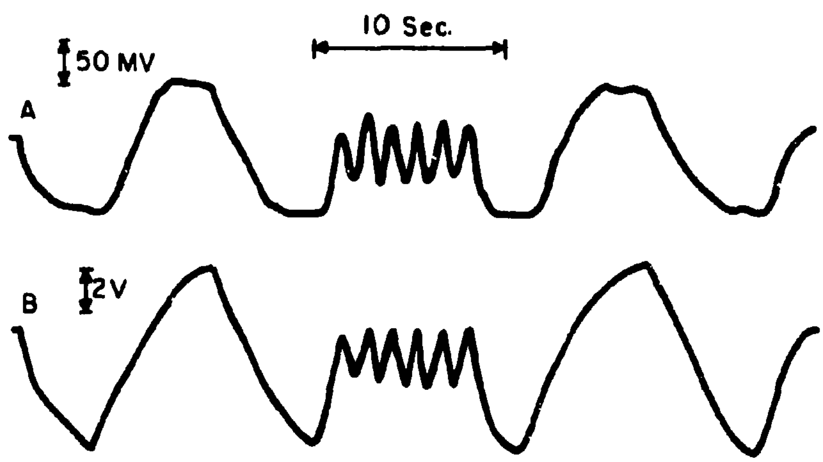

Figure 16. "Clipping" of the pneumograph output (Trace A) at high inspiratory and expiratory levels caused by the interposition of three layers of surgical gauze between the insulated electrodes and the subject's chest. Trace B is the wedge spirometer output.

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This report describes an impedance pneumograph capable of measuring quantitatively respiratory volumes. Features of this system include the use of a higher frequency (300 KHz) excitation voltage than is normally used in impedance pneumography and the use of pasteless electrodes which are insulated from the subject by a layer of polyethylene, thus forming a capacitive coupling of the electrodes to the subject and eliminating the problems associated with skin-to-electrode impedance changes. A near perfect empiric correlation was found to exist between the transthoracic impedance measured by this device and pulmonary volume.

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